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Comprehensive economic evaluations of a residential building with solar photovoltaic and battery energy storage systems: An Australian case study

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ABSTRACT

This paper presents a comprehensive framework for conducting economic analysis of a residential house along with the integration of solar photovoltaic (PV) units and battery energy storage systems (BESSs). The proposed framework is developed by considering different tariff structures of the existing energy market as well as the investment costs for the solar PV units and BESSs. In this paper, the economic evaluations are carried out based on different economic measures such as replacement cost, electricity bill, simple payback analysis, net present value, discounted payback analysis, and levelized cost of energy along with the reduction in carbon di-oxide (CO_2) emissions and grid independency. The proposed framework is implemented on an Australian residential building by considering different real-time operating scenarios. The results from the analysis demonstrate the profitability of a residential building for the investment on solar PV units and BESSs.

1. Introduction

Many households across the globe are installing solar photovoltaic (PV) systems over past few years motivated by generous gross profits and net state and/or federal government feed-in tariff schemes along with other financial incentives. The reasons behind promoting these motivational schemes are to reduce the transmission and distribution system losses and environmental pollutions [1]. Additionally, the rapidly declining cost of battery energy storage systems (BESSs) is attracting some houses to install BESSs in order to better manage and control the solar PV system for domestic usages [2,3]. The installation of solar PV units and BESSs for a residential building requires a huge amount of investments for which the residential customers are unwilling to take risks [4,5]. Thus, it is essential to conduct a comprehensive economic analysis to encourage residential consumers which is also often called as cost-benefit analysis.

The economic analysis of a green building is proposed in [6] for an Israeli office building. In [6], the cost-benefit model is developed by considering the cost to build a new energy efficient building. Though the cost-benefit model as presented in [6] is useful for constructing new green buildings, but it does not provide any idea to convert existing buildings into green buildings. The refurbishment of existing residential buildings in Catalonia is presented in [7] for selecting energy efficiency measures through the cost-benefit analysis. A thorough analysis is presented in [7] by considering different features of the building rather than considering the installation costs of solar PV and BESSs. Apart from this, a cost-effective energy saving measure is presented in [8] which mainly stresses on building information management and conducts only an energy consumption analysis. A similar approach is presented in [9] for the cost-benefit evaluation of building intelligent system by considering intangible benefits and energy consumptions. All these approaches as presented in [6–9] are mainly based on either from constructional points of view or building intelligence and do not clearly indicate the cost-benefit analysis related to the installation of solar PV and BESSs.

Several economic measures are used to assess the installation of solar PV units and BESSs in residential buildings [10]. These measures include the cost of electricity (electricity bills), levelized cost of energy (LCOE) which is also known as the grid parity, net present value (NPV), internal rate of return (IRR) or discounted payback period (DPBP), and payback period (PBP). The cost of electricity is mostly used as an economic measure to conduct the cost-benefit analysis for residential houses [11–16]. The net savings in electricity bills after installing solar PV units and BESSs can be obtained using

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Nomenclature

r_{TU}	Time-of-use rate
r_o	Off-peak rate
T_o	Off-peak period
r_s	Shoulder rate
T_s	Shoulder period
r_p	Peak rate
T_p	Peak period
$\mathcal{U}(E(\Delta t))$	Utility of energy savings
$\varepsilon(E(\Delta t))$	Expenses of energy purchases
E_{PV}	Energy generation from PV unit
E_L	Energy consumption by the load
SOC	State of charge
SOC	State of charge
SOC_{min}	Minimum state of charge
SOC_{max}	Maximum state of charge
α	Switching factor for time-of-use and flat rate
β	Switching factor for feed-in tariff
E_U	Energy utilization
E_{BC}	Battery stored energy due to charging
E_{BD}	Battery supplied energy due to discharging
E_E	Excess energy
$\mathcal{U}(E_{U,TU})$	Cost of energy utilization in time-of-use rate
$\mathcal{U}(E_{U,FT})$	Cost of energy utilization in flat rate
$\mathcal{U}(E_{E,FD})$	Cost of energy utilization in feed-in tariff
E_S	Energy shortage
$\varepsilon(E_{S,FT}(\Delta t))$	Cost of energy purchase in flat rate
$\varepsilon(E_{S,TU}(\Delta t))$	Cost of energy purchase in time-of-use rate
$\mathcal{U}(E_{L,FT}(\Delta t))$	Cost of utilizing energy from the PV unit in flat rate
$\mathcal{U}(E_{L,TU}(\Delta t))$	Cost of utilizing energy from the PV unit in time-of-use rate
$\mathcal{U}(E_{BD,FT}(\Delta t))$	Cost of utilizing energy from the BESS unit in flat rate
$\mathcal{U}(E_{BD,TU}(\Delta t))$	Cost of utilizing energy from the BESS unit in time-of-use rate
C_T	Investment costs
C_{OM}	Operational costs
C_{PV}	Capital cost of solar PV systems
C_M	Cost of solar PV modules
C_I	Cost of inverters
R_M	Rating of solar PV modules
R_I	Rating of inverters
ρ_M	Per unit cost for the solar panel module in $\kW
ρ_I	Per unit cost of the inverter in $\kW
$R_{BESS,P}$	Peak power rating of the BESS
$R_{BESS,E}$	Energy rating of the BESS
ρ_P	Per unit power of the BESS in $\kW
ρ_E	Per unit energy cost of the BESS in $\kWh
FV	Future value
PV	Present value
r	Interest rate
n	Life-time
T	Total period
$Bill_{NR}$	Electricity bill without renewable
$Bill_{PV}$	Electricity bill with PV units
$Bill_{PVB}$	Electricity bill with PV units and BESSs
S_{PV}	Net savings with PV units
S_{PVB}	Net savings with PV units and BESSs
PBP_{PV}	Payback period with PV units
PBP_{PVB}	Payback period with PV units and BESSs
y	Period of the project
NPV	Net present value
CF	Cash flow
S	Net savings
E	Annual energy generation
DPBP	Discounted payback period
LCOE	Levelized cost of energy
W_{NR}	CO_2 emissions without PV units
W_{PV}	CO_2 emissions with PV units
R_{CO_2}	Reduction in CO_2 emissions

the cost of electricity. In [11–14,17], the technology cost related to the solar PV units and BESSs are considered to calculate the cost of electricity while storage cost, storage round trip efficiency, and life time are considered in [15]. On the other hand, several factors such as discount rate, solar irradiation, technology costs as well as operation and maintenance costs are considered in [15]. However, the feed-in tariff and premium for self-consumptions are not considered in [11–15]. Recently, a cost-benefit analysis is conducted in [18] in terms of electricity costs for a residential building by considering both feed-in tariff and premium for self-consumptions. However, the total investment costs for the house is too high in [18] as the house is equipped with a combined heat power (CHP) generator and solar concentrator. This clearly indicates the necessity of considering other measures for conducting cost-benefit analysis.

The combination of electricity costs and LCOE is used in [19] where the technology costs as well as the energy consumption patterns of the building are considered. The feed-in tariff and self-consumption premiums are also considered in [19] in order to conduct the cost-benefit analysis. The cost of electricity and NPV are used in [20] as economic measures to conduct the cost-benefit analysis. Moreover, the technology cost and the prices for electricity are considered in [20] along with the feed-in tariff. The technology costs and feed-in tariff are considered in [21] to conduct the cost-benefit analysis through IRR and PBP. Similar economic measures are considered in [22] though there are no indications about the tariff structures. The cost-benefit analysis frameworks as presented in [11–22] consider only one tariff structure, where indicated, which is either the time-of-use (ToU) or flat rate. But this is not the case for the real-world situation as different houses may select different tariff structures or even the same house may choose different pricing options through dynamic pricing plans (DPPs). In such cases, the approaches so far presented in this paper cannot provide any solutions.

The utility companies have developed exciting DPPs to encourage consumers through changing their consumption patterns or choosing different electricity pricing schemes [23]. The Australian energy market is an ideal example of DPPs where the electricity retailers provide different options to the consumers. In Australian energy market, these DPPs include three different tariffs such as ToU, flat rate, shoulder rate, and feed-in tariff [24]. Through DPPs, the customers are encouraged to reap financial benefits by utilizing offered incentives. At the same time, the consumers are also encouraged to efficiently manage the energy consumption while attempting to flatten the overall load profile. Thus, DPPs are beneficial for both consumers and utilities through saving costs and reducing peak-to-average ratio, respectively. Therefore, it is essential to consider all different tariff structures in order to conduct the cost-benefit analysis.

In recent years, the reduction in carbon di-oxide (CO_2) gas emissions is also considered as an improvement of economic factors as many countries are imposing carbon taxes. In [25], the potential impact of global warming on residential buildings in UAE is